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ORIGINAL ARTICLE

Microfacies analysis, depositional settings and reservoir investigation of Early Eocene Chorgali Formation exposed at Eastern Salt Range, Upper Indus Basin, Pakistan

Muhammad Fahad[1] · Mumtaz Ali Khan[1] · Jabir Hussain[1] · Adeeb Ahmed[1] · Mustafa Yar[2]

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Abstract
The Early Eocene Chorgali Formation, Eastern Salt Range has been investigated for microfacies, depositional and reservoir analyses. The Formation consists of light to dark gray limestone with shale intercalations. The identified microfacies of Chorgali Formation are: (a) Foraminiferal bioclastic wackestone, (b) Benthonic foram-rich wackestone, (c) Bioclastic wacke-packestone, and (d) Miliolidal bioclastic wackestone. These microfacies represent wackestone depositional fabric with major faunal assemblage of Nummulites, Lockhartia, Assilina, and Miliolids. The environment of deposition is consistent with distal middle to proximal inner ramp settings. Diagenetically, the Chorgali Formation is affected by neomorphism, micritization, rare sparitization, dissolution, microfracturing, chemical and mechanical compactions and very rare dolomitization. Among these features, dissolution, micro-fracturing are the porosity-enhancing processes that increase the reservoir potentiality of the Chorgali Formation. The core plug porosity and permeability values of surface samples are 3.91% and 0.244 mD, respectively, depicting that surface sample porosities are comparatively lower than the subsurface porosities. The petrophysical analysis of the two wells (Balkassar-OXY-01 and Turkwal Deep-01) established that Eocene Chorgali Formation with dominant limestone facies at certain depths has suitable reservoir parameters. The Early Eocene Chorgali Formation of Pakistan depicts analogous features to that of the Early Eocene Naredi Formation (shale and carbonate member) of the Kutch Basin of Western India, based on the Nummulites and Assilina species, depositional fabric and depositional environment. This endeavor may be implied to the future studies of the Chorgali Formation as a hydrocarbon reservoir either in some unexplored oil or gas fields or to extend the limits of already explored fields along with the academic insights.

Keywords Eocene · Chorgali · Microfacies · Salt Range · Upper Indus Basin · Reservoir

Introduction

Eocene carbonates are known for the sufficient hydrocarbon production in the Potwar sub-basin of the Upper Indus Basin of Pakistan. The first success for commercial oil discovery dates to 1915 at Khaur (Northern Potwar sub-basin, Punjab) by Attock Oil Company from Eocene and Miocene reservoir rocks (Khan et al. 1986). Subsequent discoveries made include Dhulian (1935), Balkassar (1944), Joya Mair (1944) fields, in the Potwar sub-basin establishing the potential of the highly fractured Eocene limestone (Kadri 1995). Onwards made discoveries comprised Karsal (1956), Meyal (1968), Toot (1968), Adhi (1978), Dakhni (1983) and Dhurnal (1984) fields (Khan et al. 1986). The investigated outcrop section (Fig. 1) is the part of Salt Range, Potwar sub-basin. The study area lies in eastern Salt Range (Fig. 1) and it is outlined by latitude 32° 30′ and 33° 45′ N and longitude 71° 30′ and 74° 0′ E.

The Eocene carbonates have a very well exposure across the Salt Range and formations of Eocene successions include Nammal, Sakesar and Chorgali formations forming the extensively studied and focused Paleogene sedimentary successions. The earliest studies include the work of Gill (1953) who investigated the faunal assemblages in the Bhadrar beds of the Salt Range and correlated the facies variation in rock units exposed in Lower Indus Basin and

✉ Mumtaz Ali Khan
mumtazkhan@bui.edu.pk

1 Earth and Environmental Sciences, Bahria University Islamabad Campus, E-8, Shangrilla Road, Islamabad, Pakistan

2 FATA University, FR Kohat, Akhurwal, Pakistan

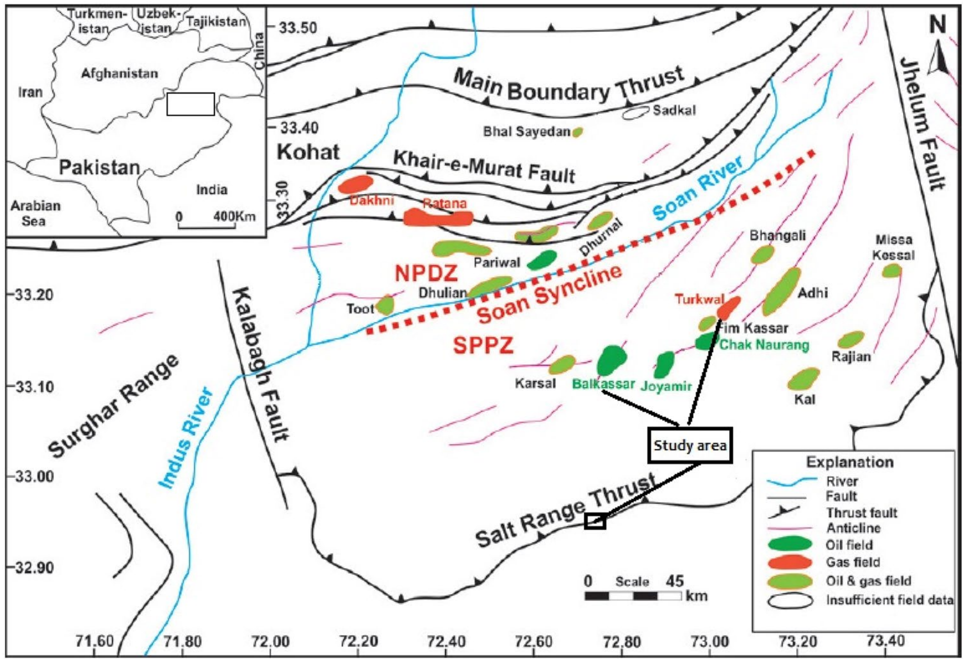

Fig. 1 Location map of the study area (shown by a rectangular inset) and the investigated wells of the Chorgali Formation with generalized oil and gas field of Potwar Basin in northern Pakistan (after Riaz et al. 2019, Chen and Khan 2009; Kadri 1995; Kemal 1991 and Khan et al. 1986)

Kohat-Potwar sub-basins. Based on such faunal assemblages, Gill (1953), Iqbal (1969), Fatmi (1973), Shah (1977) and Baqri et al (1997) assigned the age to the Bhadrar beds as early Eocene. The contributory work in regards of microfacies and environment of depositional of Chorgali Formation in Chorgali Pass, Khair-e-Murat range, Pakistan was carried out by Durrani (1999). The detailed work (unpublished PhD dissertation) of Mujtaba (2001) was emphasized to infer the depositional environment of Chorgali Formation and to find out diagenetic changes for the development of secondary porosity within the dolomitic and limestone facies of the formation within the Salt Range and Potwar sub-basin. The sedimentological and diagenetic evolution studies of the Chorgali Formation were carried out by Benchilla et al (2002) in the Salt Range. Ghazi et al (2010; 2014) worked on foraminiferal assemblages of larger benthic of Chorgali Formation and microfacies analysis along with interpretation of depositional environment of the Chorgali Formation exposed at sections of Khajula, Tatral, Badshah Poor and Karuli in the Salt Range and the depositional environment was regarded as inner shelf. Awais (2015) studied the effect of digenesis on the quality of reservoir in Chorgali Formation, Gali jagir, Khair-e-Murat and the investigations of the (Jamalian and Adabi 2015) include microfacies and diagenetic fabric of the Chorgali Formation in localities of Bhuchal Kalan, Kallar Kahar and Salt Range. The most recent work done by Awais et al (2018) is the relating of petrophysical parameters to petrographic interpretations in carbonates of the Chorgali Formation, Potwar sub-basin, Pakistan. Since the exposure of the Chorgali Formation at eastern Salt Range is in bits and pieces and there is a perplexity in correlation and at the outcrop level studies as here most of the outcrops have no exposure of upper and lower contacts. Hence, the present study will contribute to understanding various allochemical constituents, evaluating of the faunal assemblages and the diagenetic fabrics of the Chorgali Formation to interpret the depositional environment based on the microfacies identified, coupled with correlation of both surface and subsurface reservoir aspects of the Chorgali Formation (Fig. 2).

General geology of the study area

The Paleogene epoch is one of the imperative ages that is characterized by collision of the Indian plate with the Asian plate, onset of Himalayan events of orogenesis and evolution of Himalayan foreland basin (Singh 2013). The collision between Indian and Eurasian plates which is in turn called Himalayan collision has resulted in formation of major tectonic framework in north Pakistan and this under-thrusting of the Indian Plate below the Eurasian plate is still continued (Jayalakshmi and Raghukanth 2015). The main tectonic fabrics of northern Pakistan encompass Main Karakoram Thrust (MKT) or Shyok suture zone which separates rocks of Eurasian plate from the rocks of Kohistan Island Arc, main mantle thrust (MMT) or Indus suture zone displaces the rocks of Kohistan Island Arc on top of Higher Himalayan rocks of the Indian Plate origin, main central thrust (MCT) separates the rocks of Higher Himalayas from Lesser Himalayas and the Main Boundary Thrust (MBT) that is present between rocks of Lesser Himalayas and Sub Himalayas and Salt Ranges Thrust (SRT) (Seeber et al 1981). Apart from

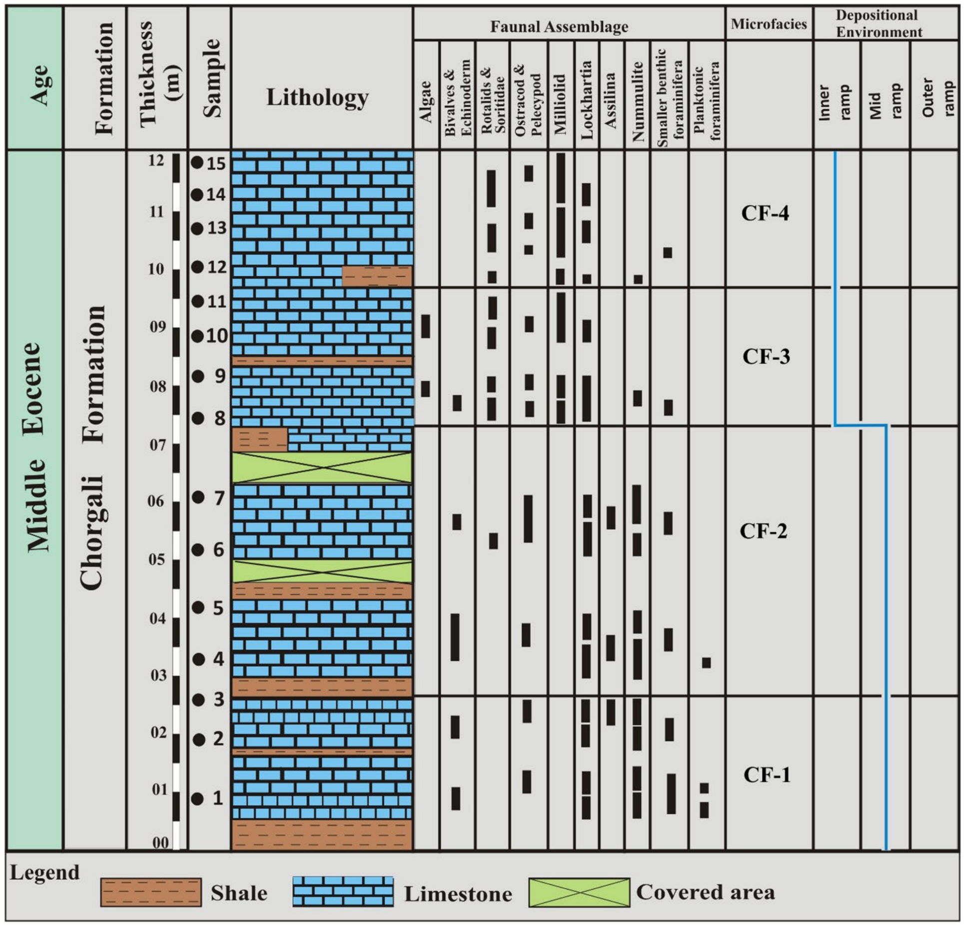

Fig. 2 A measured stratigraphic column showing vertical contribution of microfacies of the Chorgali Formation at Buchal Kalan section, eastern salt range

the main tectonic zones, the study area constitutes the part of the Salt Range tectonostratigraphic zone. This tectonic zone extends about 200 km and it is about 85 km wide and exposing a wide spectrum of sedimentary successions from the Precambrian to Quaternary age (except Ordovician to Carboniferous) along the Salt Range Thrust (Kazmi and Jan 1997).

The Salt Range is a surface exposure along the Salt Range Thrust (SRT) and indeed it is one of the southern-most and recent manifestations of Himalayan collision. It is a thin-skinned fold and thrust belt in which Paleozoic to Recent sediments are shortened over a ductile substrate of thick Eo-Cambrian evaporites of the Salt Range Formation (Lillie et al 1987). Eastern and western peripheries of the Salt Range is marked by left lateral Jehlum and right lateral Kalabagh faults, towards south and north by salt range thrust (SRT) and Soan Syncline or MBT (main boundary thrust), respectively. According to Gee and Gee (1989), the Salt Range encompasses a couple of characterizing features that include the occurrence of the thick salt deposits and some of regional and local scale events of non-depositional or unconformities ranging from Eocambrian to Pleistocene in age. In the Salt Range, the initial unconformity is recognized between the conglomeratic deposits of overlying Tobra Formation and the Cambrian succession, the second stratigraphic break which is marked by the laterite deposits exists between the Jurassic Samana Suk Formation and the Palaeocene Hangu Formation (Fatmi, 1973; Kadri 1995; Kazmi and Jan 1997; Ghazi et al. 2014). The third main stratigraphic break occurs between the Early Eocene and Mio-Pliocene sequence and the last event of non-deposition occurs between the Mio-Pliocene sediments and the Recent Conglomerates (Kadri 1995; Kazmi and Jan 1997; Ghazi et al. 2012). The exposed sedimentary successions of the Salt Range rang from Precambrian to Miocene in which the oldest rock unit is being the Salt Range Formation and the youngest rock units are the Recent Conglomerates (Ghazi et al. 2014).

The Chorgali Formation constitutes the younger sequence in the Chharat Group which is exposed across the Salt Range and the Chorgali Formation in the study area is located at the eastern Salt Range and lithologically the study formation encompasses mainly of limestone with some shale beds and intercalations of the shale. The employed tool of microfacies analysis coupled with the faunal assemblage of larger benthic foraminifera and other fossils, the inferred environment of deposition of the Chorgali Formation at the study area is a homoclinal ramp of middle to inner ramp settings. The ramp setting of the Chorgali Formation is buttressed by prevailed higher abundance of micritic matrix in identified microfacies, absence of re-sedimentation and reef building organisms and grainstone microfacies which are more consistent with a ramp setting than a shelf (Mehr and Adabi 2014).

Materials and methods

For the current study, the outcrop of the Chorgali Formation (Fig. 3) exposed at eastern Salt Range was logged and sampled. During the field work, vital field features of the Chorgali Formation were observed and noted including lithological variations, nature of bedding and other megascopic features, such as color, texture, nodularity, etc. A total of 20 samples were collected from compact limestone beds of the exposed outcrop. Laboratory tests coupled with laboratory studies were carried out (e.g. outcrop samples were thin-sectioned and then thoroughly analyzed and studied under the polarizing microscope). The allochems and orthochems constituents were analyzed and identified by employing the Dunham's (1962) classification. The percentages of the allochems and orthochems were calculated through the visual estimations by considering the chart of (Scholle and Ulmer-Scholle 2003) for estimating abundances of constituents in thin section, and then taking the average values of the present allochems and ratio of orthochems. For the reservoir aspect, the petrophysical data consisting of geophysical logs of two wells (Turkwal Deep-01 and Balkassar OXY-01) were attained to evaluate the reservoir characteristics and to

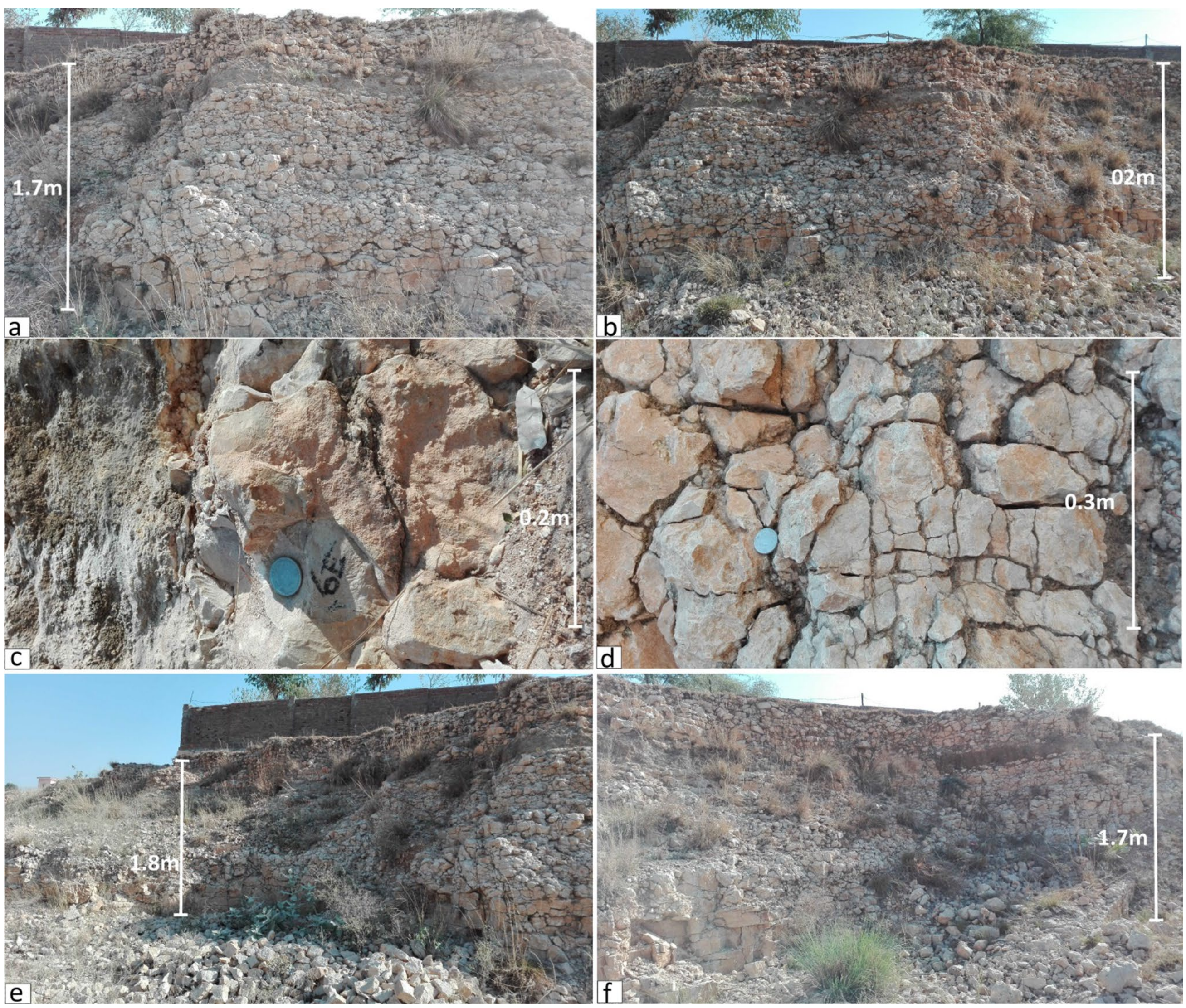

Fig. 3 An outcrop view of the Chorgali Formation exposed at Buchal Kalan section of eastern Salt Range

compare the surface and subsurface reservoir parameters of the Chorgali Formation. Moreover, core plug permeability and porosity analyses were conducted on the total of 10 outcrop samples of Chorgali Formation to correlate and compare the values of surface samples with sub-surface logs.

Results

Lithostratigraphy

The exposed Chorgali Formation at the study area is mainly composed of the two dominant lithologies that are mainly limestones followed by the interbedded shale and shale intercalations. In the eastern Salt Range, the Chorgali Formation is found in bits and pieces and the outcrop exposure is confusing as its upper and basal contact are not exposed in most of the places (Jamalian and Adabi 2015). The basal part and the basal contact are not exposed to observation at some parts as it has been eroded or removed for the construction (Fig. 3). The soft and calcareous greenish-gray shale lithology constitutes the basal part of the formation (Fig. 4) and then there is light gray planar- to nodular-bedded limestone that weathers to yellow and gray. Middle parts are thin-bedded limestones that vary from the basal part owing to the presence of larger foraminifera with interbedded dark gray shale. Upper part of the Chorgali Formation comprises tan to light pink, thin- to medium-bedded fractured limestone and patchy limestone sequences with dark gray shale intercalations in between. The limestone of the Chorgali formation at the basal part is argillaceous and overall, the limestone is compact, nodular, fine-grained and crystalline in nature having concoidal fracture and calcite veins. The basal shale and interbedded shale coupled with shale intercalations are light to dark gray in color and are calcareous and friable in nature.

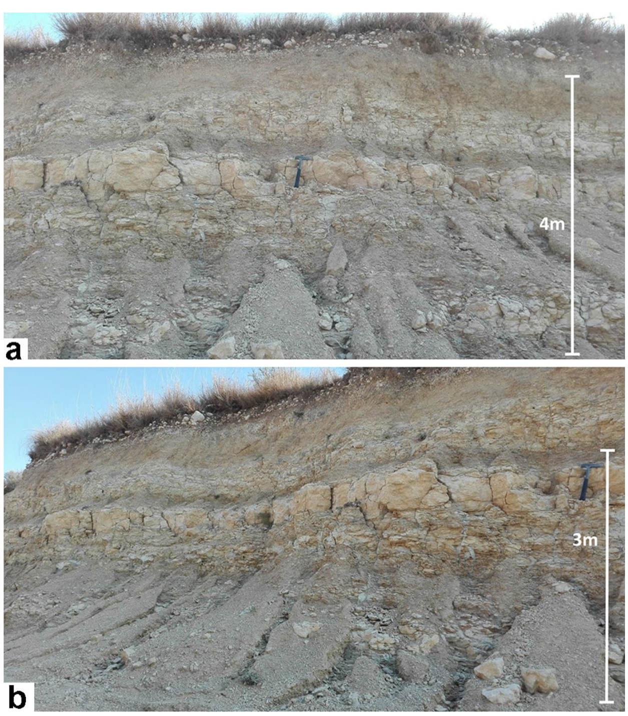

Fig. 4 The outcrop view with basal shale unit of the Chorgali Formation exposed at Buchal Kalan section of eastern salt range

Microfacies analysis

Based on the petrographic analysis and outcrop studies, four microfacies are erected including the types and percentages of allochems, diagenetic features and fossil assemblages. The upper and lower contacts of the Chorgali Formation are not exposed to observation. The petrographic study revealed that the larger benthic foraminifera are the dominant distributed fossil assemblages and the predominant microscopic depositional fabric is of wackestone in the Chorgali Formation; the detailed description of the microfacies is as follows:

Foraminiferal bioclastic wackestone microfacies (CF-1)

This microfacies, at the outcrop level, represents fine- to medium-grained light to dark gray limestone with minor inter-beds of shale. Petrographically, these microfacies are characterized by diverse bioclasts of the bivalve mollusk and rare bio-debris of echinoderms (echinoid spines) with presence of the genera of larger benthic foraminifers including Nummulites, Lockhartia, rare Soritidae and Assilina with non-existent eroded planktonic foraminifers and ostracods (Fig. 5). Apart from these allochems, the orthochems of microfacies mainly have the micritic matrix with diagenetic features including micritic envelop formation, internal micritization, microfractures filling by calcite, neomorphism with rarer pyrite precipitation and mechanical compaction. The allochems of the microfacies constitute around 23–25%; with the relative average abundance of the Nummulites (4%), Lockhartia (3%), echinoderms (2%), pelecypods (1%), soritidae and planktons (1–2%) and bio-debris (12%). The present matrix forms the predominant fraction of 77–75% that makes the allochem to matrix ratio up about 1:3 of the wackestone depositional fabric as per the Dunham's classification (1962) of carbonates.

Benthonic foram-rich wackestone microfacies (CF-2)

The CF-2 microfacies has a slight variation in the lithology and grain size. It is mainly medium- to fine-grained light gray limestone with some rust patches due to iron oxidation along with an inter-bed of shale. The petrographic composition of this microfacies encompasses

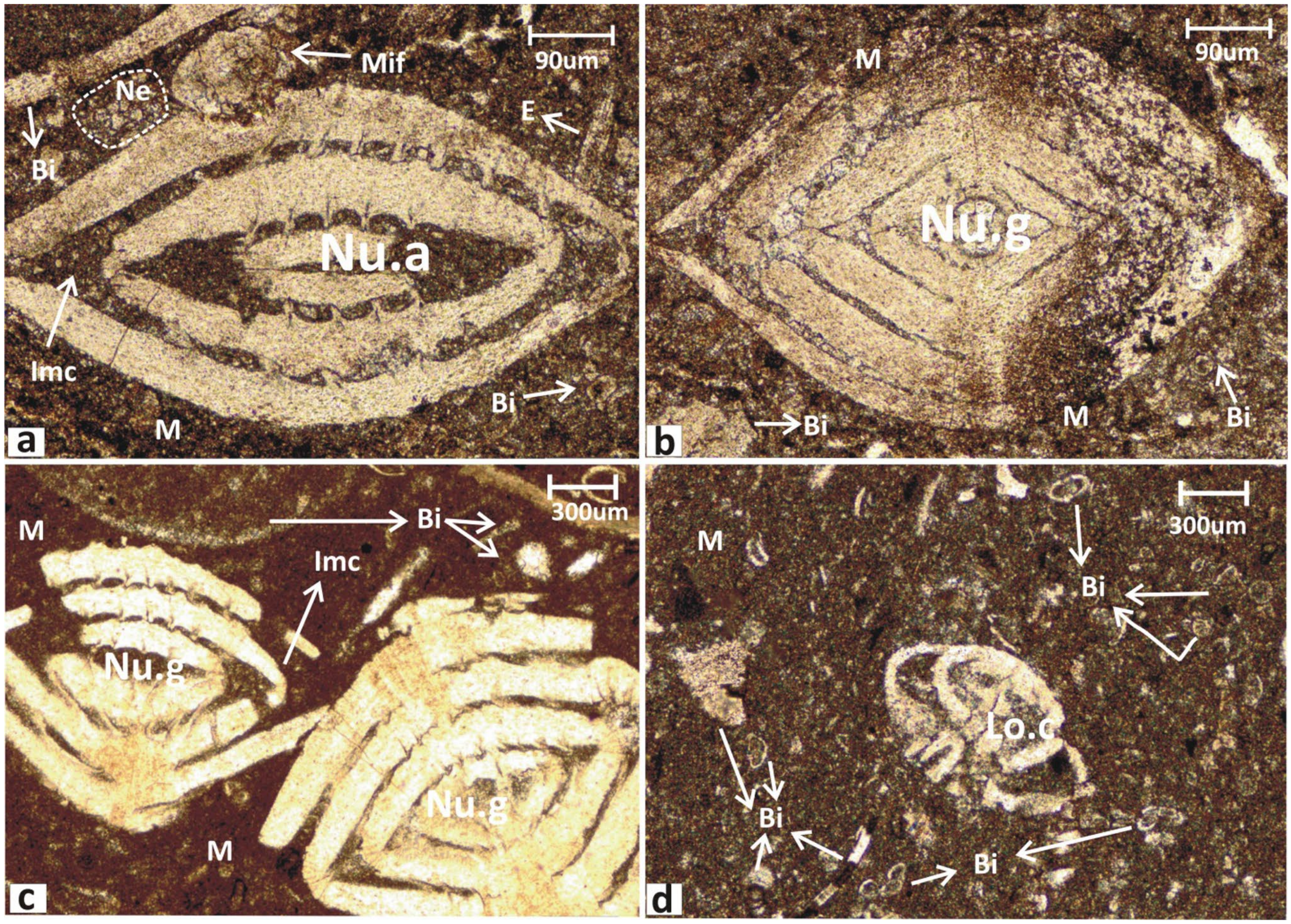

Fig. 5 Representative photomicrographs of the Foraminiferal bioclastic wackestone microfacies (CF-1); a represents Nummulites atacicus (Nu.a), Echinoderm spine (E), bioclasts (Bi), micritic/ micritization (M), micritized fossil (Mif), neomorphism (Ne) and internal micritization (Imc); b shows Nummulites globulus (Nu.g), micrite/micritization (M) and biolclast (Bi); c displays Nummulites globulus (Nu.g), micrite/micritization (M), bioclast (Bi) and d represents Lockhartia conditi sp. (Lo.c), biolclast (Bi) and micrite/micritization (M)

mainly genera of larger benthic foraminifers like Nummulites, Lockhartia, and rare Assilina and poorly preserved Aleveolina and miliolid coupled with bio-debris of ostracods and echinoderms (Fig. 6). The orthochem is represented mainly by matrix and very rare sparite with the diagenetic features including neomorphism, internal micritization, sparitization, dissolution, stylolytic swarms and microfractures filled by calcite. The allochems of the CF-2 microfacies include the average abundance of the Nummulites (4%), Lockhartia (4%), Assilina (2%), Alveolina (1%), miliolids (2%), echinoderm and ostracod (1–2%) and bioclasts (12–14%) forming an overall ratio of allochem to matrix 1:3. This microfacies is devoid of any planktonic foraminifers that correspond to the deeper settings.

Bioclastic wacke-packestone microfacies (CF-3)

This microfacies constitutes the medium-grained pale gray to light gray limestone with very minor shale intercalations. CF-3 microfacies petrographically, contains the fossil assemblages of species of Rotalia, Soritidae, Lockhartia and uniserial foraminifers and the other skeletal fossils echinoderm, pelecypod with algae and miliolids along with the dominance of bio-debris of Rotalia, echinoderms (echinoid spine) and ostracods. This microfacies has rare to nonexistent larger benthic foraminifers like Nummulites, Assilina rather contains shallower fauna like Rotalia, soritidae, miliolids and algae (Fig. 7). In orthochems, this microfacies has mainly micritic matrix and some patches of sparite are also present. The observed diagenetic features of this microfacies

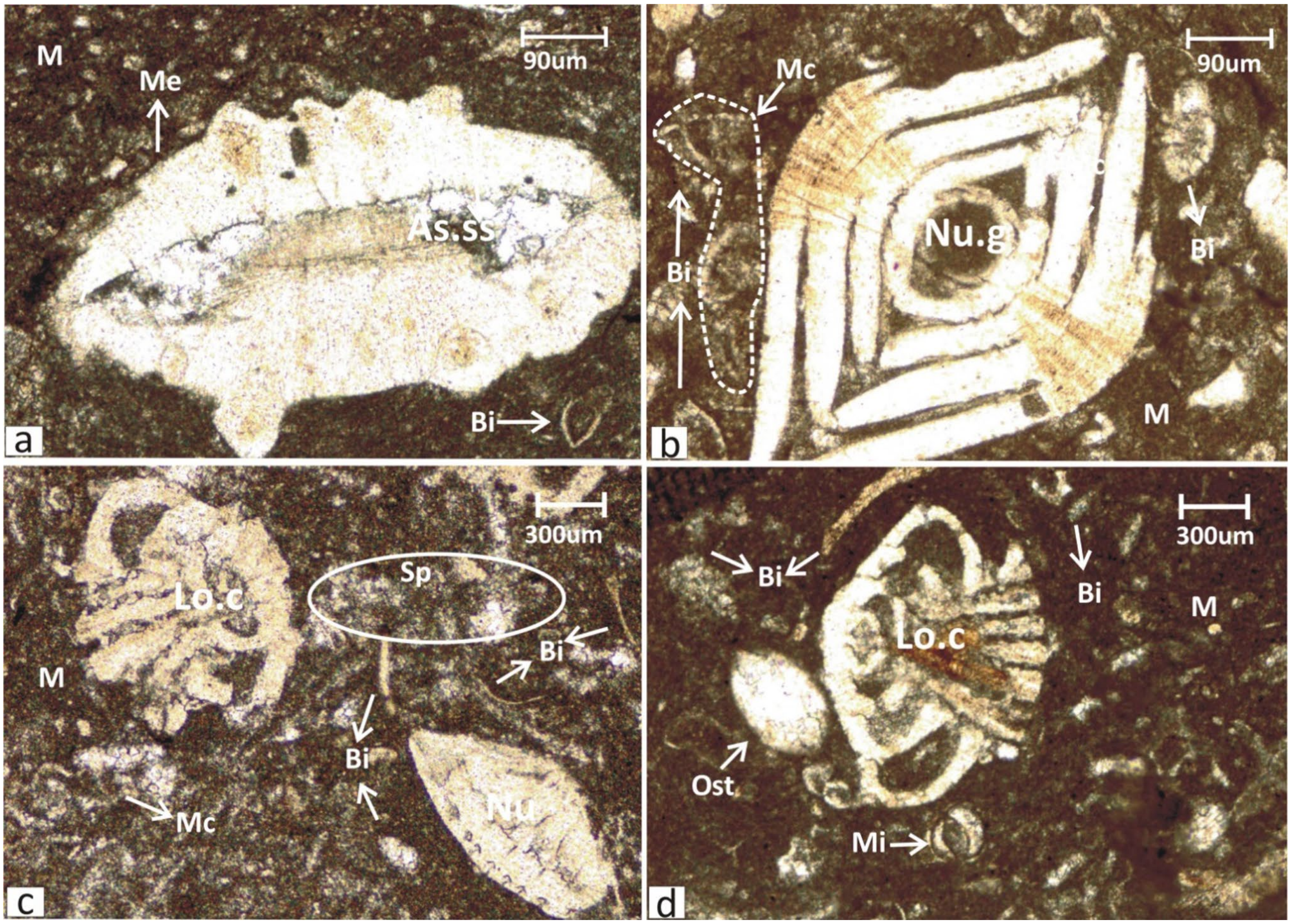

Fig. 6 Representative photomicrographs of the Benthonic foram-rich wackestone microfacies (CF-2); **a** represents Assilina subspinosa (As.ss), micritic envelope (Me), bioclasts (Bi), micritic/ micritization (M), **b** shows Nummulites globulus (Nu.g), micrite/micritization (M) biolclast (Bi) and micritized clasts (Mc); c displays Lockhartia conditi sp. (Lo.c), Nummulites sp. (Nu), biolclast (Bi) and micrite/micritization (M), sparitization (Sp), micritized clasts (Mc); and **d** represents Lockhartia conditi sp. (Lo.c), ostracod (Ost), miliolid (Mi), biolclast (Bi) and micrite/micritization (M),

include micritization, sparitization, stylolitization and stylolytic swarm's formation and microfractures filling by calcite. The average estimated abundance of allochems include Lockhartia (4%), miliolids (5%), Rotalia (4%), soritidae (4%), ostracod (3%), pelecypod (2%), algae (2%) with bioclasts around (14–16%) and the overall allochems-to-matrix ratio is 1:2:5.

Miliolidal bioclastic wackestone microfacies (CF-4)

The CF-4 microfacies is represented by medium-grained, light gray limestone mainly and it represents the top-most samples taken from the top of the studied formation. This microfacies is mainly characterized by the presence of miliolids with lockhartia and other fossil assemblage like ostracod, Rotalia and echinoderm with the presence of algae along with biolclasts of Rotalia, echinoderm (echinoid spines), pelecypod and Lockhartia. The CF-4 microfacies lacks the larger benthic foraminifers except some *Lockhartia* sp. and it dominates shallower faunal assemblage like miliolids, soritidae, osrtacod, rare Rotalia and algae (Fig. 8). The orthochem is mainly the micritic matrix with the diagenetic features of dissolution, micritization, acicular cementation, stylolitization, and microfractures filled by calcite. The average estimated abundance of faunal assemblage includes miliolids (7%), Lockhartia (4%), soritidae (3%), Rotalia (2%) ostracod and pelecypod (1–2%) and bioclast abundance is around (9–10%) and the overall allochems-to-matrix ratio remains 1:3.

Depositional environment and discussion

Open marine platform conditions existed during Early Eocene time (Ghazi et al. 2014) and caused the deposition of Chharat Group in the Salt Range that comprises of the Nammal Formation, the Sakesar Limestone and the Chorgali

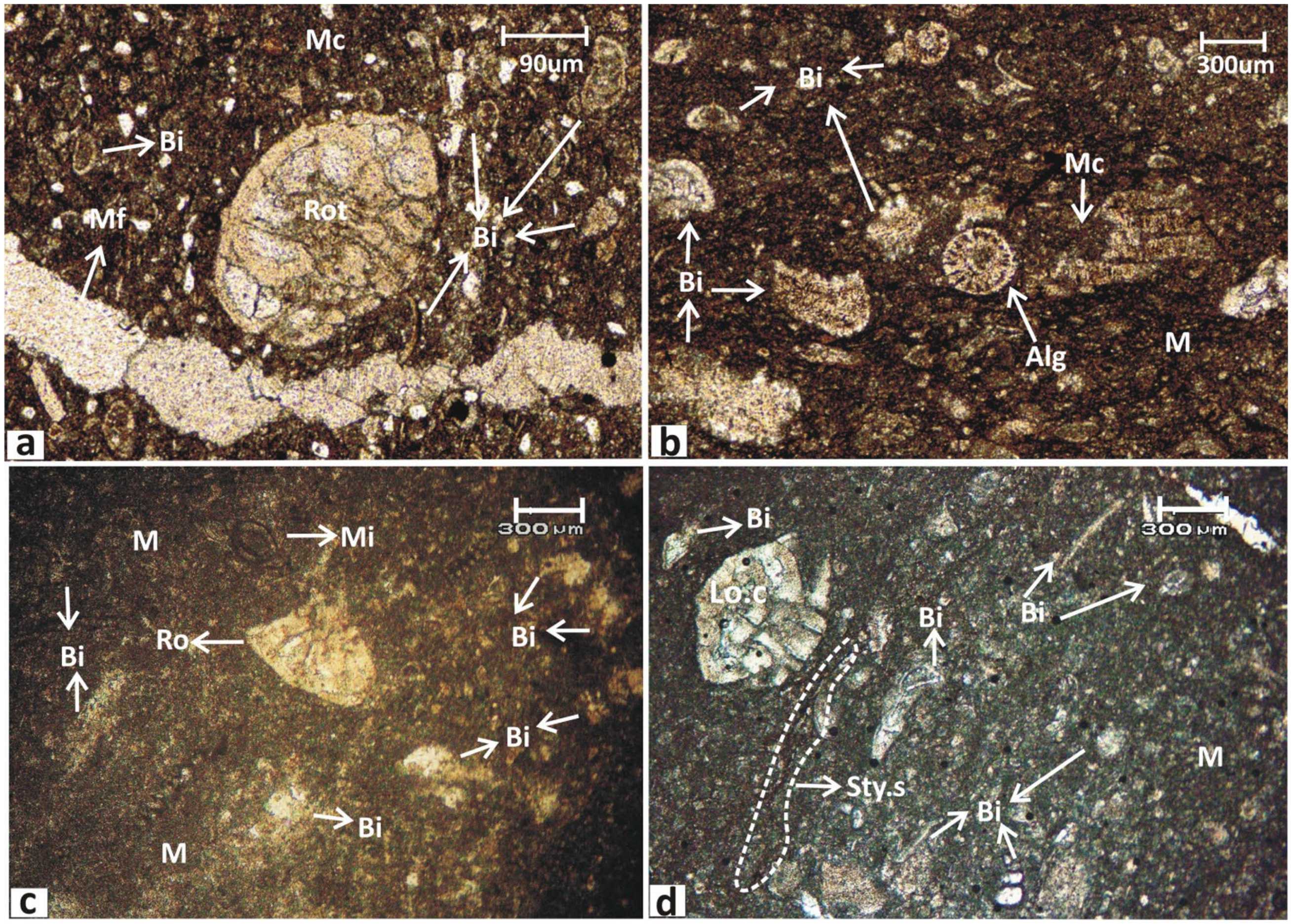

Fig. 7 Representative photomicrographs of the Bioclastic wacke-packestone microfacies (CF-3); **a** represents Rotalia(Ro), microfracture filled with calcite (Mf), bioclasts (Bi), micritized clast (Mc), **b** shows Algae (Alg), micrite/micritization (M), micritized clast (Mc) and biolclast (Bi); **c** displays Rotalia (Ro), Miliolid (Mi), biolclast (Bi) and micrite/micritization (M); and **d** represents Lockhartia conditi sp. (Lo.c), biolclast (Bi). Stylolitic swarms (Sty.s) and micrite/micritization (M)

Formation. Lithologically, the Chorgali Formation constitutes mainly limestone and shale facies and biostratigraphically, it encompasses the abundance of larger benthic foraminifers (LBFs) followed by shallower faunal and smaller benthic foraminifers with rare to non-existent planktonic foraminifers. Among the larger benthic foraminifers, the most abundant faunal assemblage includes the genera of Nummulites coupled with Lockhartia and miliolid along with the smaller fraction of smaller benthic foraminifers. In CF-1 and CF-2 microfacies, there is an association and abundance of Nummulites with Lockhartia and very rare Assilina coupled with non-existent planktonic foraminifers. The abundance of planktonic foraminifera is found in open marine pelagic water, while, the abundance of benthic foraminifera is found in shallow marine environment (Van Der Zwaan 1982; Morkhoven and Berggren 1986). The Nummulites accumulations are the evidence of high sediment production rates in middle ramp waters (Pomar 2001; Barattolo et al 2007) and the *Lockhartia* sp. represents inner to middle ramp settings (Racey 1994). The association of Nummulites sp. with *Assilina* sp. indicates deeper inner to middle ramp depositional conditions (Buxton and Pedley 1989; Racey 2001; Beavington-Penney and Racey 2004; Vaziri-Moghaddam et al 2006; Adabi et al 2008; Payros et al 2010). However, the high diversity of Nummulites sp. Lockhartia sp. with rare Assilina sp. and very rare planktons dispersed in micritic matrix indicate that CF-1 and CF-2 microfacies were deposited in low-energy conditions of middle ramp settings (Fig. 2).

The microfacies CF-3 and CF-4 mainly have relatively shallower faunal assemblages of Lockhartia sp., Miliolids and poorly preserved Alveolina coupled with Rotaliids and Soritiidae with rare presence of larger and smaller benthic foraminifera. According to Hallock and Glenn (1986), lagoonal environments are often dominated by imperforate foraminifera (e.g., miliolids, soritiidae and alveolinidae and small rotaliines) (Fig. 9). By the early Eocene, soritiidae with imperforated walls prevail in restricted

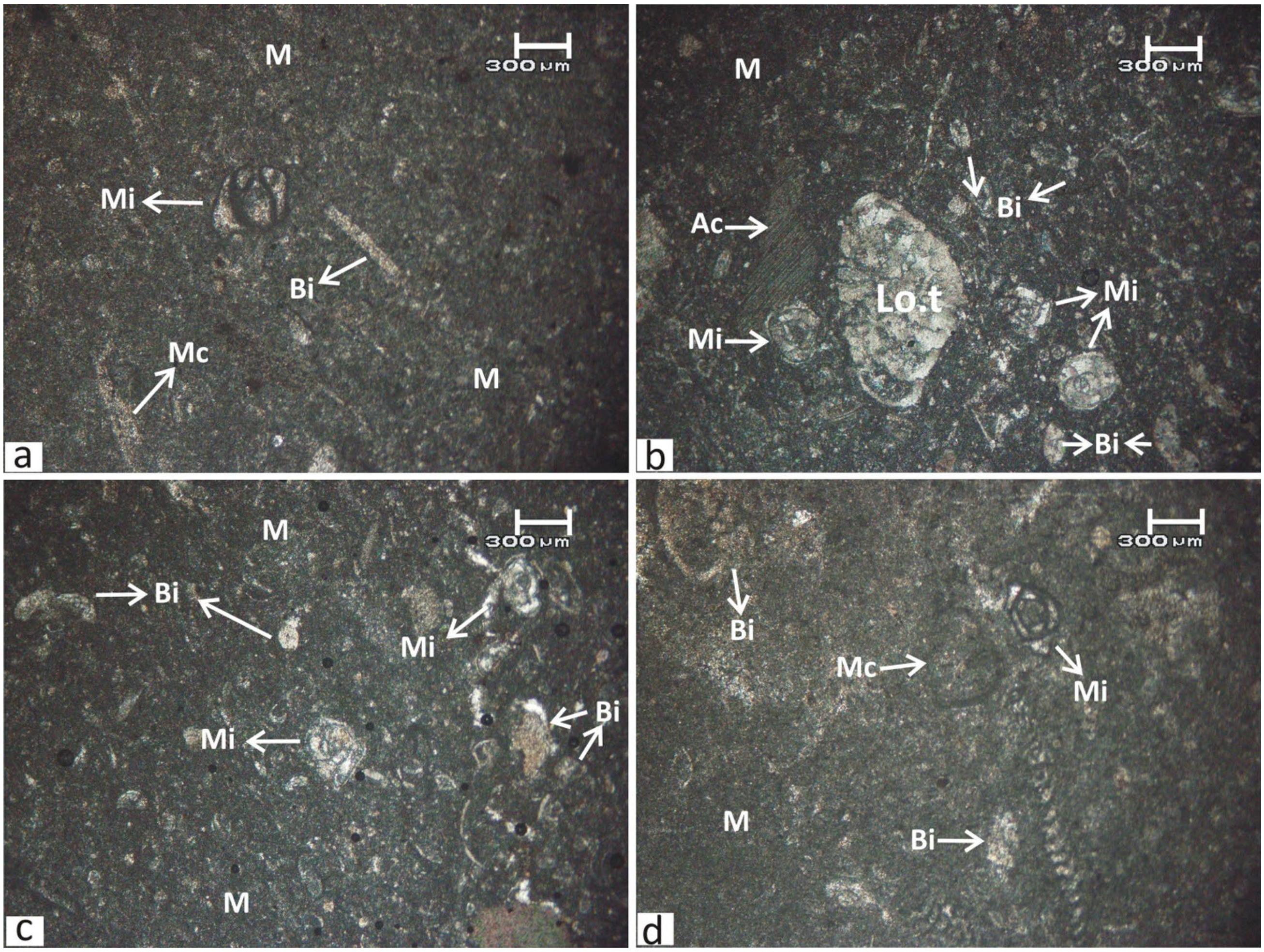

Fig. 8 Representative photomicrographs of the Miliolidal bioclastic wackestone microfacies (CF-4); **a** displays Miliolid (Mi), bioclasts (Bi), micritized clast (Mc) and micrite/micritization (M), **b** shows Lockhartia tipperi (Lo.t) Miliolid (Mi), biolclast (Bi), Acicular cement (Ac) and micrite/micritization (M); **c** displays Miliolid (Mi), biolclast (Bi) and micrite/micritization (M); and **d** represents Miliolid (Mi), biolclast (Bi). Micritized clast (Mc) and micrite/micritization (M)

platform and lagoon environment (Hallock and Glenn 1986; BouDagher-Fadel 2008) and assemblages of small Rotalinae with robust ornamented shells and a perforated wall and miliolids with imperforate wall indicate a very shallow-water lagoon (Hallock and Glenn 1986). Moreover, the association of Lockhartia sp. and Miliolids with rare dasycladale green algae indicates inner ramp setting of low water turbulence and restricted conditions (Racey 1994; Beavington-Penney et al 2006; Adabi et al 2008). The miliolids dwell at calm and quite shallow-water conditions and their great dominance suggests nutrient-rich and lagoonal marine conditions of inner ramp (Racey 1994; Beavington-Penney et al 2006; Adabi et al 2008; Swei and Tucker 2012; Mehr and Adabi 2014). So, based on dominant matrix-supported rock fabric, the moderate to low diversity of foraminifera, presence of restricted marine fauna suggest that the CF-3 and CF-4 microfacies were deposited in inner ramp lagoonal settings (Fig. 9).

Based on the detailed microfacies analysis coupled with association of faunal assemblage of larger benthic foraminifera and other fossils, the inferred environment of deposition of the Chorgali Formation at the study area is a homoclinal ramp of middle to inner ramp settings (Fig. 9). The presence of larger benthonic foraminifera in the Chorgali Formation at the study area demonstrates the conditions of tropical to subtropical climate during deposition of the Chorgali Formation as compared to other Tethyan carbonate ramps (Buxton and Pedley 1989). Based on identified microfacies associations in the Chorgali Formation, the ramp setting for the Chorgali Formation is suggested relying on the evidence of prevailed higher abundance of micritic matrix in all microfacies, absence of grain stone microfacies and reef building organisms, lack of re-sedimentation and the basin-ward gradual

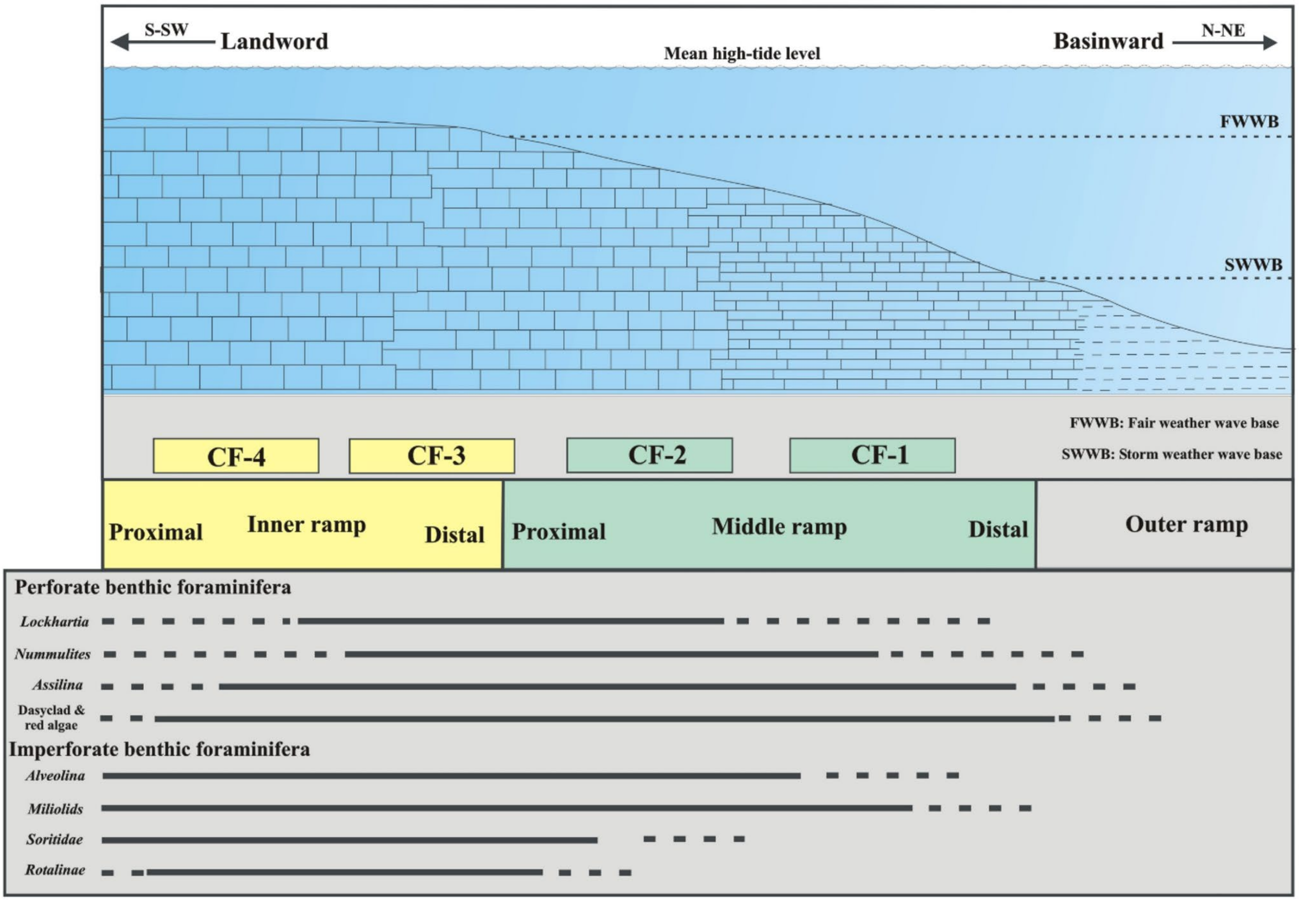

Fig. 9 A schematic distribution of recognized perforate and imperforate benthic foraminifera along carbonate ramp (after Hallock and Glenn 1986; Racey 1994; Gilham and Bristow 1998; Beavington-Penney and Racey 2004) along with the proposed depositional model for the Chorgali Formation at Buchal Kalan section, Eastern Salt Range

trend of shallow platform; are more consistent with a ramp setting than a shelf (Mehr and Adabi 2014). The presence of faunal assemblage reflects that the deposition of the Chorgali Formation took place at the retro-gradational phase.

In Kutch Basin of Western India, Naredi Formation of early Eocene is an analogous sedimentary sequence to the Chorgali Formation of Pakistan, as the Naredi Formation is also comprised of shale and limestone (Khanolkar and Saraswati 2019). The upper carbonate member of the Naredi Formation is more commonly comparable with the Chorgali Formation as the upper part comprises of larger foraminifera including Nummulites and Assilina like A. spinosa (Biswas and Raju 1973; Biswas 1992) owing to which early Eocene age was assigned. The Naredi Formation is subcategorized into three members including the Gypsiferous Shale Member, Assilina Limestone Member and the upper member was named as unfossiliferous Ferruginous Claystone Member (Khanolkar and Saraswati 2019). The outcrops of the Naredi Formation have yielded species of Nummulites and Assilina, such as spinosa and laxispira. The presence of fossil assemblage at the upper carbonate member like Assilina, Nummulites, Rotalids (Srivastava and Singh 2017) reflects the similarity with the outcrop and microfacies attributes of the Chorgali Formation. The carbonates of the Naredi Formation developed in a peri-cratonic basin on the western margin of India and the carbonate facies identified include Dirty yellow bioclastic wackestone and Brownish yellow Assilina packstone corresponding to inner to middle ramp settings. (Srivastava and Singh 2017). The Naredi Formation in the Kutch Basin represents shale, claystone facies, wackestone and packstone microfacies coupled with presence of the Nummulites and Assilina which is consistent with the Inner to middle ramp depositional environment corresponding to that of the Chorgali Formation (Srivastava and Singh 2017).

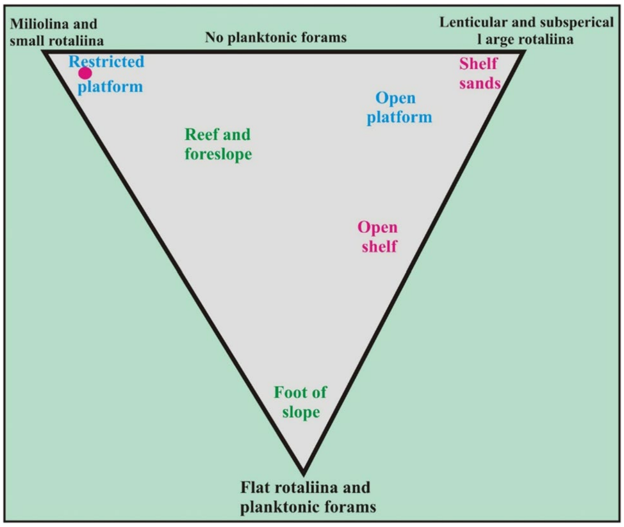

Fig. 10 A Ternary plot based on the percentage of Miliolina and Rotaliina versus planktonic foraminifera (after Murray 1991)

Reservoir Investigation of the Chorgali Formation

Eocene carbonates are known as the most prolific reservoirs in the Upper Indus basin. Characterization of the carbonate reservoirs depends on porosity, permeability, capillary pressure, fluid saturation and the type of fluid present (Fig. 10). Petrographically, the Chorgali Formation depicts that its original composition and the texture are transformed by neomorphism, micritization, cementation, dissolution, microfractures, stylolitization and rare dolomitization (Fig. 11). The effects of these petrographic features are given in Table 1

Understanding the relationship between the diagenetic fabrics and the distribution of the pore size is fundamental to reservoir evaluation. Diagenetic processes are of great importance owing to their effect on the depositional fabric of the rocks, their enhancing or reducing impacts or efficacy on the pore volume, fluid flow efficiency, and petrophysical potentiality of the analyzed rocks (Nabway and Kassab 2014). Based on sedimentary-petrographic analysis, the diagenetic history and evolution of the Chorgali Formation were affected by a series of processes including micritization and development of micritic envelopes, dissolution, neomorphism, cementation, physical and chemical compaction, fracturing, veins formation, pressure dissolution and very rare dolomitization (Fig. 11; Table 1). Some of the diagenetic processes are closely associated to depositional texture and mineralogy (e.g., compaction, cementation, selective dissolution), whereas the others (like dolomitization,) are more related to groundwater (brine) flow (Lucia et al. 1999). Among the diagenetic processes of the Chorgali Formation, the dissolution, dolomitization, and microfracturing are the most important porosity-enhancing processes (Table1). In contrast, the micritization, cementation, neomorphism, veins formation and both chemical compaction including stylolitization (partly or completely) and mechanical compaction (partly or completely) are the vital porosity-reducing processes (Table 1).

Among the porosity-reducing processes, micritization is the most common diagenetic process that has affected the skeletal fragments from partial to complete obliteration of original depositional fabric in most of the wackestones microfacies of the Chorgali Formation. According to Li et al. 2017, porosity reduces with increase of calcite cement whereas permeability reduces with increase of calcite content when permeability is greater than 1 mD, yet no linear relations exists when permeability is less than 1 mD. Thus, micritization can result in reduction of permeability, as the micrite can fill the pore throats (Taghavi et al. 2006). Cementation causes loss of pore volume with progressive cementation and pore filling (Nabway and Kassab 2014) and in the Chorgali Formation, calcite cement is the most common cement either of predominance of micritic matrix and/or as sparite to microsparite cements. The identified cements include acicular, fibrous and sytaxial overgrowth cements (Fig. 11a). Neomorphism (Fig. 5a) can diminish the reservoir porosity and aragonite to calcite transformation causes an enhancement in total rock volume of 8%, and porosity decreases by 8% (Fig. 11d; Selley 2000). The mechanical compaction (Fig. 11c) results in a contraction of rock volume or tightening of the rock pattern that can diminish the reservoir quality. Stylolitization (Fig. 11e, f) thoroughly destroys porosity and eliminates permeability in dolomites, yet on the microstructural scale it can enhance horizontal permeability (Hassan 2007). The chemical compaction can be in the form of solution seams that can obstruct fluid circulation (Ehrenberg et al. 2006; Moradpour et al. 2008) and can trigger partial or complete destruction of porosity. Moreover, it can eliminate permeability due to pressure dissolution where pores are either developed as primary or during earlier diagenetic history (Ferket et al. 2003).

Among the diagenetic fabrics, dissolution is one of porosity-enhancing processes include which is a destructive in nature and it increases porosity and permeability of the rocks and has major control on reservoir development (Fig. 11b; Moore1989; Jamalian and Adabi 2015). Dolomitization causes to form intercrystalline porosity and it can enhance the reservoir quality and during dolomitization, the conversion of calcite to dolomite occurs which enhances the porosity by 13% (Chilingar and Terry 1964). Microfractures are the channels or pathways that can pave the way to flow the fluid and it can add both to the porosity and/or permeability of the Chorgali Formation (Table 1).

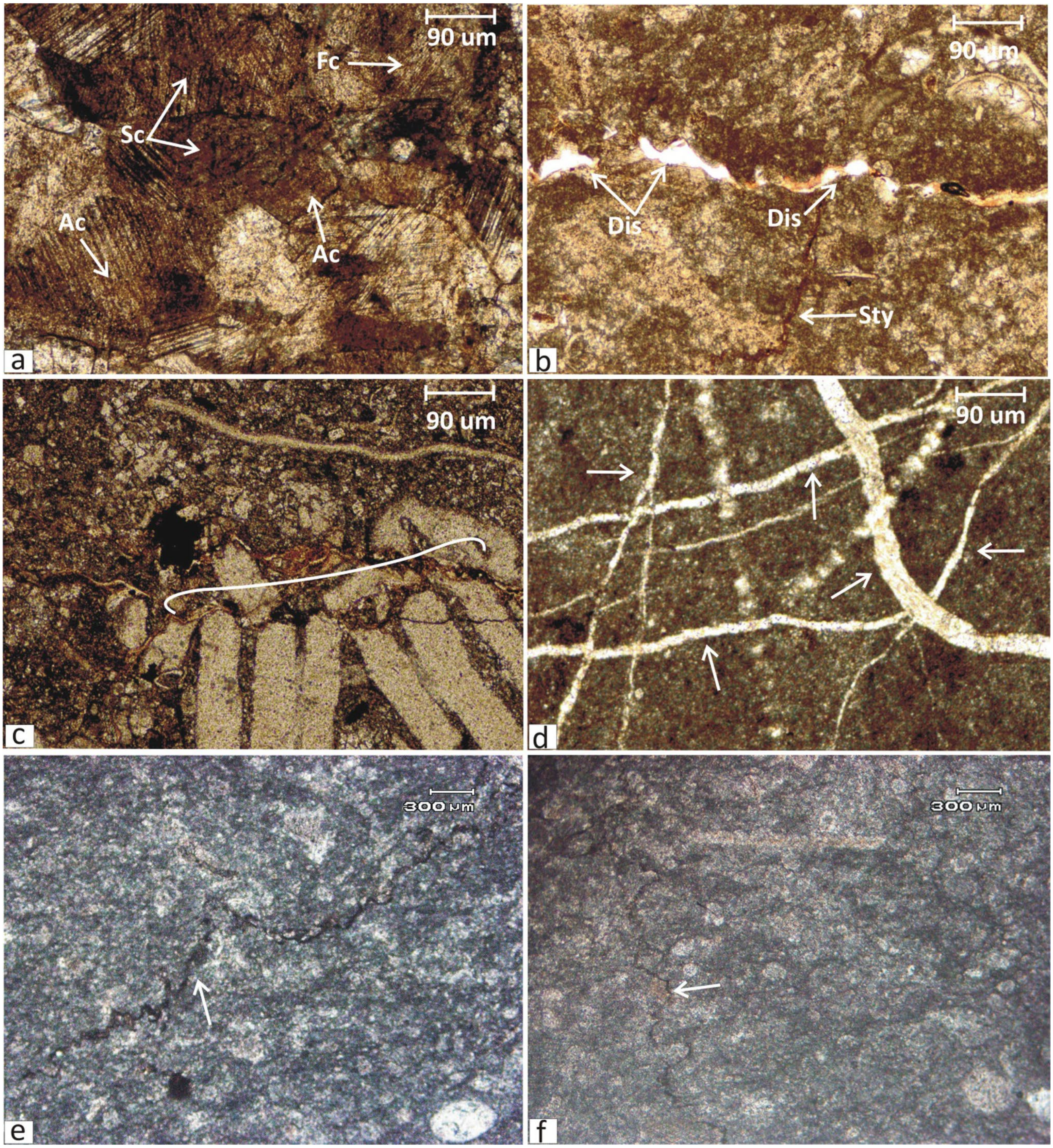

Fig. 11 The representative photomicrographs of the diagenetic features of the Chorgali Formation at the study area; **a** represents types of cementation that are Acicular cement (Ac), Fibrous cement (Fc) and sytaxial overgrowth cement (Sc), **b** displays the dissolution (Dis), chemical compaction that is stylolitization (Sty), **c** shows mechanical compaction, **d** represents microfractures of calcite (shown by arrows' head) depicting dislocations, e and f represent stylolites (shown by the pointed arrows)

Plug porosity plug permeability analyses

Plug porosity test was conducted on seven outcrop samples. Minimum and maximum values of the porosity test obtained from the samples range 0.25–14.13% (Table 2). For the porosity test, a core plug was obtained from the outcrop sample that underwent 500 psi of overburden pressure. The core plug permeability test was conducted on the seven

Table 1 The diagenetic features and their impacts on the reservoir quality of the Chorgali Formation at the study area

Diagenetic process	Reservoir quality		
	Increased	Decreased	Partly enhanced or reduced
Micritization		↓	
Dolomitization	↑		
Dissolution	↑		
Neomorphism		↓	
Cementation		↓	
Fracturing	↑		
Chemical compaction			↑ ↓
Mechanical compaction		↓	↑
Calcitic veins		↓	

outcrop samples initially and to validate the result, three more outcrop samples of Chorgali Formation were processed at 400 psi of overburden pressure and the range of permeability is 0.009–1.63 mD (Table 2).

Porosity comparison at surface and subsurface

For determination and correlation of surface porosity with sub-surface porosity (effective porosity), a well-logging tool is employed, and such parameters are interpreted through wire line logs of nearest wells named as Turkwal Deep-01 and Balkassar OXY-01. Petrophysical experiment is an imperative tool to elucidate the petrophysical parameters and petrophysical properties including permeability, porosity, fluid saturation, areal extent and thickness of reservoir and is so crucial to the oil and gas industry (Saadu and Nwankwo 2018). Evaluation of the permeability and porosity of subsurface reservoirs is a basic goal of petroleum and water industries (Worthington 1997) and determination of the petrophysical parameters is a crucial process in the evaluation of hydrocarbon volume (Saadu and Nwankwo 2018). The maximum performance of any reservoir is driven by these petrophysical parameters (Saadu and Nwankwo 2018), thus this study has also employed the petrophysical tool to delineate the reservoir parameters of the Chorgali Formation among which the most vital ones are the porosity and permeability. The average porosity calculated for surface samples is 2.86% and permeability of 0.188 mD that are relatively lower than the sub-surface. The subsurface calculated average effective porosity using wireline logs in Balkasar-Oxy-01 and Turkwal-deep-01 are in the range of 10–11.27%, respectively.

Petrophysical analysis of Turkwal Deep-01 and Balkassar-OXY-01

For petrophysical analysis of Turkwal Deep-01 and Balkassar-OXY-01, different formulas were used to

Table 2 Porosity and permeability results of the outcrop samples of the Chorgali Formation gathered at equal space of interval vertically

Sample No	Porosity (%)	Permeability(mD)	Remarks	Interval
1	14.13	0.011	Micro-fractured	Top
2	0.50	0.010		
3	1.22	0.009		
4	0.25	0.015		
5	0.31	0.013		
6	0.32	0.014		
7	10.70	1.638	Micro-fractured	Bottom
8	0.57	0.011		Top
9	0.29	0.014	Micro-fractured	Middle
10	0.35	0.013		Bottom

Table 3 A table showing petrophysical calculated values of the Chorgali Formation at the wells Turkwal Deep-01 and Balkassar-OXY-1

Chorgali formation			
Section/wells	Turkwal deep-01	Balkassar-OXY-1	Outcrop
Total thickness (m)	54.40	45.72	7
Average porosity (%)	13.90	11.41	3.92
Average effective porosity (%)	11.27	10.05	
Average permeability (mD)			0.24
Shale volume (%)	20.25	25.66	24.74

calculate average effective porosities. By applying the cut-off on shale volume (20%), porosity (6%) and water saturation (50%), no prolific hydrocarbon bearing zone was found that can be economically viable. However, the porosity calculated in the subsurface is comparatively higher as compared to the surface. The quantitative petrophysical calculations are shown in Table 3.

Both Turkwal Deep-01 and Balkassar-OXY-01 have lithological variations between limestone and shale intervals. Limestone is a compact matrix which has high resistivity and low porosity. Fractures in limestone can increase the borehole rugosity. Shale on the other hand is a loose matrix which shows low resistivity and high porosity. Shale is a brittle rock which breaks and increases the borehole size while drilling (Fig. 12).

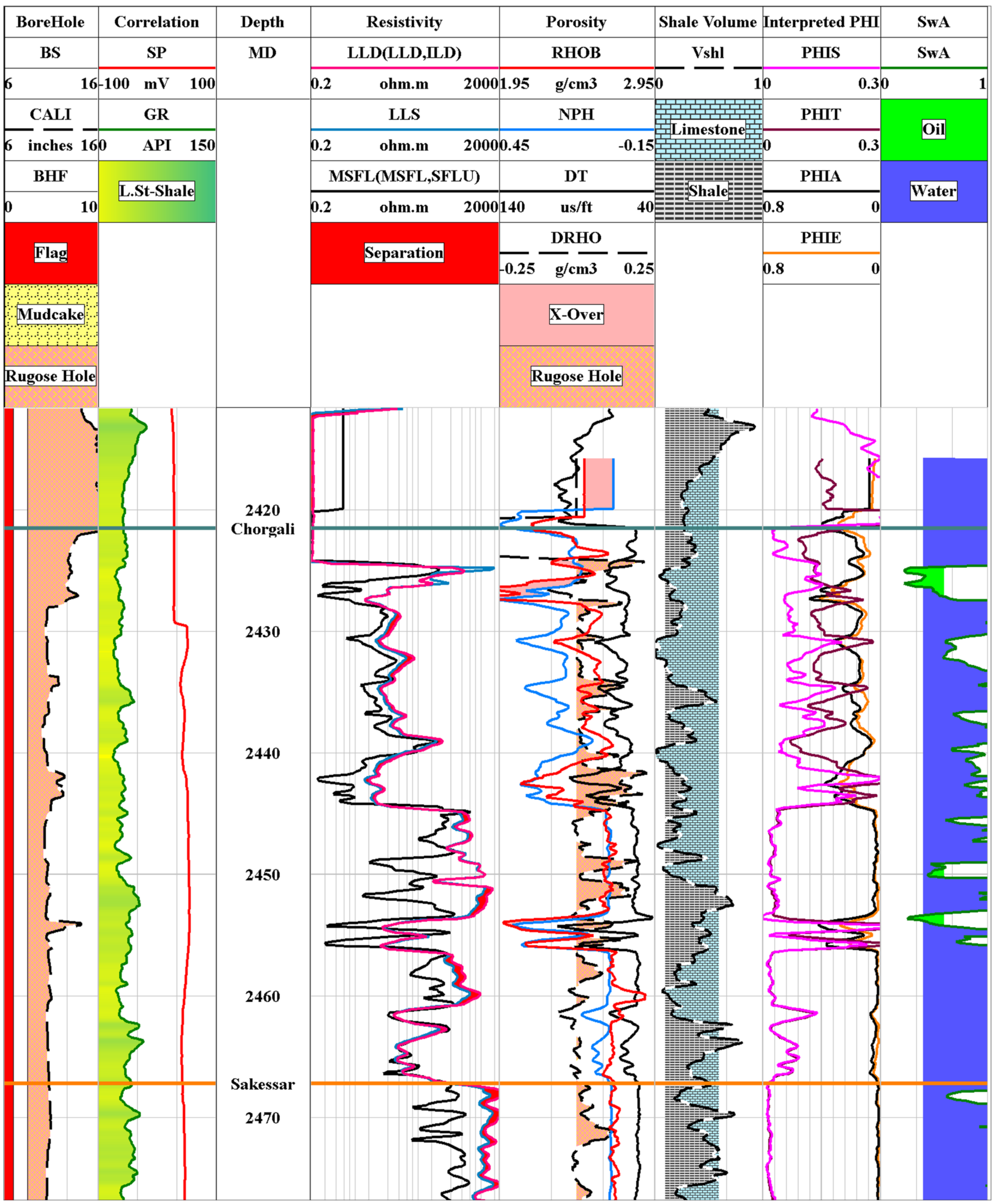

Fig. 12 A log view of the Chorgali Formation in Balkassar-OXY-01

In Balkassar-OXY-01, caliper log is not gaged and density log has low values at certain depths. Density corrected log (DRHO) also confirms borehole rugosity. This rugose hole attests loose matrix material and secondary porosity due to fractures. Average effective porosity is computed using neutron and sonic log which measures transit interval time. At top and middle intervals of the formation encountered in the well, shale volume is high, showing loose uncompact

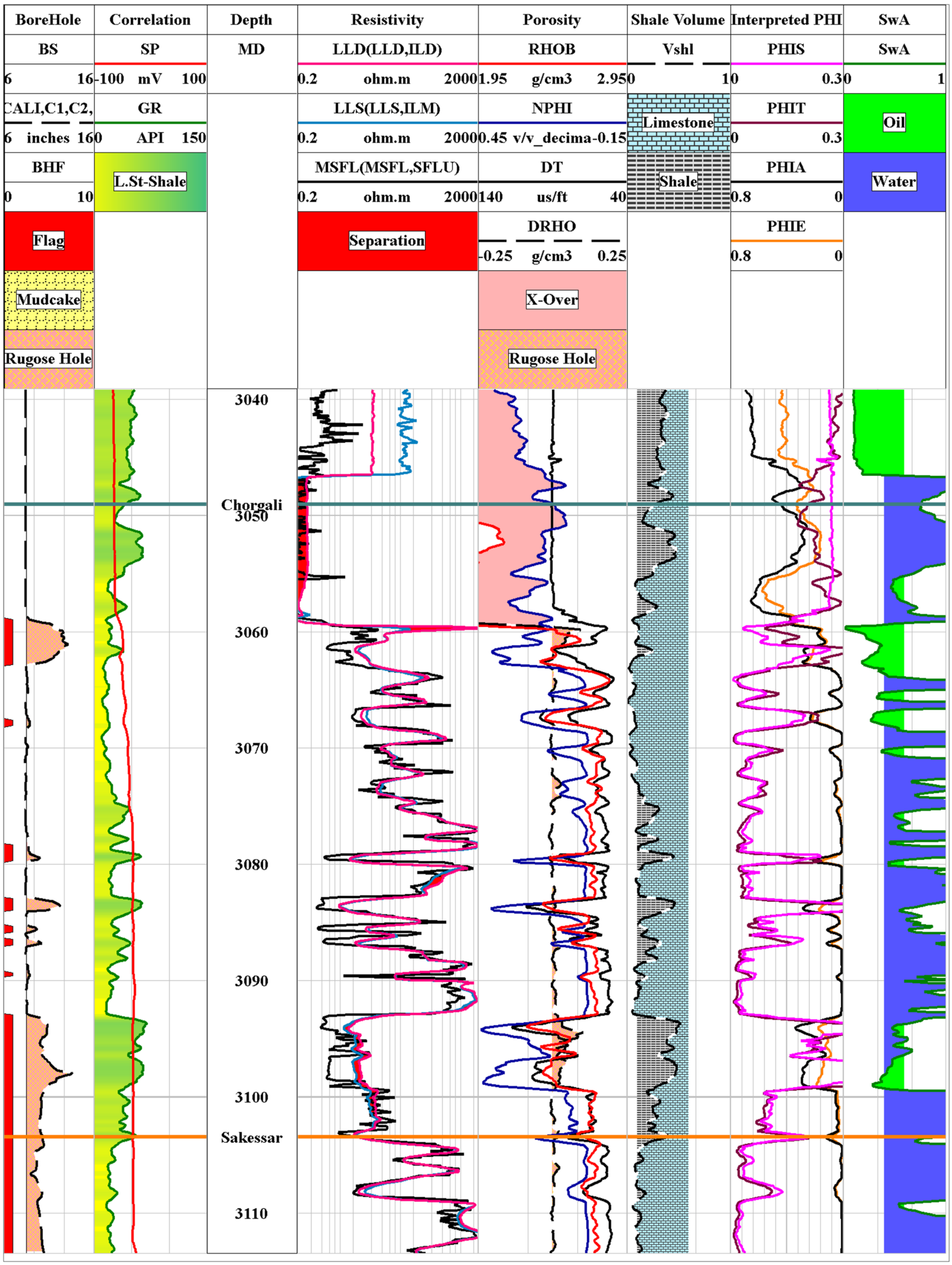

Fig. 13 A log view of the Chorgali Formation in Turkwal Deep-01

lithology i.e. shale. Lower volume of shale shows limestone matrix which is compact with low porosity and high resistivity at depth interval of 2045–2055 m.

Turkwal Deep-01 (Fig. 13) also has some lithological variations between limestone and shale intervals. Limestone facies are compact, but they show low shale volume, high resistivity and possess low porosity. In comparison, shaly facies are loose and depict low resistivity and density, and high porosity thus increasing the overall formation average porosity.

Hence, based on the petrophysical analysis of the two wells, it can be inferred that at certain depths there are suitable petrophysical parameters in the Chorgali Formation to act as a reservoir.

Conclusion

The Chorgali Formation mainly represents light to dark gray limestone with thin shale inter-beds. The identified microfacies represent mainly wackestone depositional fabric and faunal assemblage of the Chorgali Formation include mainly larger benthic foraminifera of genera Nummulites, Lockhartia, rare Assilina, shallow benthic foraminfera of Miliolids, poorly preserved Alveolina and other fossils including soritidae, rotaliidae, mollusks, ostracods and echinoderms. The identified four microfacies of the Chorgali Formation are: (a) Foraminiferal bioclastic wackestone microfacies (CF-1); (b) Benthonic foram-rich wackestone microfacies (CF-2); (c) Bioclastic wacke-packestone microfacies (CF-3) and Miliolidal bioclastic wackestone microfacies (CF-4). Based on the microfacies identified, the environment of deposition of the Chorgali Formation is suggested to be distal middle ramp to proximal inner ramp settings. The association of Miliolina and Rotaliina versus planktonic foraminifera depicts that the Chorgali Formation was deposited on a restricted carbonate platform. The presence of faunal assemblage reflects that the deposition of the Chorgali Formation took place at the retrogradational phase. The Chorgali Formation of Upper Indus basin Pakistan reflects an analogous depositional fabric, Nummulites, Assilina species and depositional environment features to that of the Early Eocene Naredi Formation (shale and carbonate member) of the Kutch Basin of Western India.

Diagenetically, the Chorgali Formation is affected by neomorphism, cementation, micritization, rare sparitization, chemical compaction (stylolites), mechanical compaction, dissolution, fracturing, calcite veins formation and very rare dolomitization. Among these diagenetic features, the dissolution, dolomitization, microfracturing are the main diagenetic features that enhance the reservoir quality of the Chorgali Formation. Relying on the core plug porosity and permeability tests, the calculated porosity and permeability of the surface samples are 3.91% and 0.244 md, respectively, that depicts that surface samples porosities are relatively lower than the sub-surface. Higher porosity values in the subsurface are due to unconsolidated matrix (shale). Limestone facies are compact and porosity ranges from 1 to 2% at certain depth intervals. The petrophysical analysis of the two wells (Turkwal Deep-01 and Balkassar-OXY-01) indicates that the Chorgali Formation, at certain depths have suitable porosity to act as a reservoir in the area.

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